

The University of Chicago

STRUCTURAL GEOLOGY OF THE  
LIVINGSTON PEAK AREA,  
MONTANA

A PART OF A DISSERTATION SUBMITTED TO  
THE FACULTY OF THE DIVISION OF THE  
PHYSICAL SCIENCES IN CANDIDACY FOR  
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY  
AND PALEONTOLOGY

1936

By

EDWARD C. H. LAMMERS

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# THE STRUCTURAL GEOLOGY OF THE LIVINGSTON PEAK AREA, MONTANA

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## ABSTRACT

The Laramide structures in and adjacent to the northwestern corner of the Beartooth Mountains are described. During the early stage of the orogeny the North Snowy block of the Beartooth Range was upthrust by deep-seated compressive stresses. In the later stage a large southward-advancing overthrust sheet encountered the corner of the North Snowy block and was deformed by lateral shearing stresses set up within it. Pressure-box experiments are described in which the later-stage structures of the Livingston Peak area were duplicated in almost every detail.

## INTRODUCTION

In southern Montana and northwestern Wyoming the bold Beartooth Mountain Range rises abruptly from the broad plains of central Montana and from the more limited Bighorn basin, which is a southward embayment of the Great Plains, into the Northern Rocky Mountains. It is an arcuate uplift, whose general trend is northwest and southeast. No less imposing than its plains-facing northeast front is the western face of the range, rising steeply from the valley of the Yellowstone River. On the south and southwest the range is bounded by the Yellowstone Park structural basin, into which has been ejected an enormous amount of Tertiary volcanic material subsequently carved by erosion into the precipitous peaks of the Absaroka Mountains. Topographically and geologically the range is a unit, and one of the most important units in the structural framework of the Bighorn basin. Because it affords exceptional opportunities for studying one type of mountain-building and because of its richness in problems in many related fields, the Beartooth Range was chosen in 1930 by a group of co-operating geologists as a desirable place for intensive geological research.

The ultimate aim of this co-operative project was a better understanding of the structural development and history of this portion of the Rocky Mountains. As a part of the research program, small key areas were studied and mapped in detail by individual members of

the group, to be fitted together later in a general monograph on the whole region. Thus in July, 1933, the writer, at the suggestion of Drs. Chamberlin, Thom, and Bucher, began a study of the structure of the northwestern corner of the Beartooth Range.

The area mapped, which covers about 70 square miles, is the northwest end of the Beartooth Range between the Great Plains around Livingston, Montana, and the drainage basin of the Deep Creek tributary of the Yellowstone River on the south, and extending from a few miles west of the Yellowstone to the eastern side of



FIG. 1.—Looking southward from Mount Baldy. Graham Pass is in the foreground

Mission Peak, one of the highest points in this part of the range. It has been named the Livingston Peak area after the barren limestone peak of that name, which forms a prominent landmark for travelers approaching the range from the north. Most of the area is in the high range, but it also includes the ridges and lowlands lying immediately north and west of the mountains. The city of Livingston lies about a mile north of the boundary of the area.

During the first summer the writer, in collaboration with Dr. Donald MacNeil and Dr. Dorr Skeels, of Princeton University, mapped the portion of the area lying west of the Yellowstone River. Assisted by Mr. Charles MacClintock, of the University of Illinois, the writer mapped the remainder in the field seasons of 1934 and 1935.



## STRATIGRAPHY

The formations outcropping in the district are listed in Table 1. A complete section was not measured by the writer because accurate

TABLE 1  
COLUMNAR SECTION OF THE NORTHWESTERN CORNER OF  
THE BEARTOOTH MOUNTAINS

| System        | Formation                                  | Thickness<br>in feet |
|---------------|--------------------------------------------|----------------------|
| Quaternary    | Alluvium<br>Glacial drift                  | .....                |
| Cretaceous    | Eagle formation                            | 408*                 |
|               | Telegraph Creek-Niobrara-Carlile<br>shales | 1593*                |
|               | Frontier sandstone                         | 300*                 |
|               | Mowry-Thermopolis shales                   | 895*                 |
|               | Dakota sandstone (?)                       | 88*                  |
|               | Fuson shale (?)                            | 260*                 |
|               | Lakota conglomerate (?)                    | 104*                 |
| Jurassic      | Morrison formation                         | 228*                 |
|               | Sundance formation                         | 484*                 |
| Pennsylvanian | Tensleep quartzite                         | 140†                 |
| Mississippian | Amsden formation                           | 111†                 |
|               | Madison limestone                          | 1800                 |
| Devonian      | Three Forks-Jefferson formation            | 514‡                 |
| Ordovician    | Bighorn dolomite                           | 438‡                 |
| Cambrian      | Gallatin limestone                         | 518‡                 |
|               | Gros Ventre shale                          | 290                  |
|               | Flathead quartzite                         | 180                  |
| Pre-Cambrian  | Quartzites, gneisses, and schists          | .....                |

\* Measured by C. W. Wilson, Jr., near Gardiner, Montana; cf. his "Geology of the Thrust Fault near Gardiner, Montana," *Jour. Geol.*, Vol. XLII (1934), pp. 651-52.

† Measured by H. W. Scott in the Lower Canyon of the Yellowstone River; cf. his "Studies on the Quadrant Group of Montana and Wyoming," Unpublished Doctor's thesis, Department of Geology and Paleontology, University of Chicago (1935), p. 34.

‡ Measured by C. W. Tomlinson on the ridge between Livingston Peak and Mount Baldy; cf. his "Paleozoic Stratigraphy of the Rocky Mountains," *Jour. Geol.*, Vol. XXV (1917), pp. 118-19.

measurements of most of the formations found in the area have already been made by other geologists working in the vicinity. Furthermore, structural deformation has caused considerable variation in the thickness of certain formations, and scarcity of well-exposed sections prevents a satisfactory measurement of some others.

## GENERAL REGIONAL STRUCTURE

The Beartooth Range is an arcuate structural uplift comparable in size to the Bighorn Mountains of Wyoming. The low-angle Beartooth thrust fault, which dips beneath the range along its northeastern front, and the high-angle Gardiner thrust, which dips beneath the southwest corner of the range, give to the Beartooth Mountains the appearance of a typical wedge-shaped uplift. When studied in detail, however, the range is found to be not a simple uplift but a composite uplift consisting of three well-defined units or blocks. During the uplift the North and South Snowy blocks, which make up the western third of the range, were tilted to the northeast, whereas the larger Beartooth Plateau block, which forms the central and southeastern parts of the range, was tilted to the southwest. As a result of this differential tilting there is a reversal in the asymmetry of the range at the northwestern edge of the Beartooth Plateau block. Without exception the minor structures have the same asymmetry as that of the block with which they are associated.

The North Snowy block is the most sharply defined of all the blocks. Along its western side it is bounded by a high-angle normal fault, well exposed at its northern end but passing beneath the alluvium of the Yellowstone Valley farther south-southwest. Elevation of the block along this fault is greatest at its southern end near the mouth of Mill Creek, about 25 miles south of Livingston. The block is separated from the South Snowy block on the southwest and the Beartooth Plateau block on the southeast by a zone of high-angle faults, which trends approximately east and west from the mouth of Mill Creek to the Stillwater River Canyon on the northeast front of the mountains, about 40 miles east-southeast of Livingston. Toward the eastern end of this fault zone the North Snowy block has been depressed with respect to the adjoining Beartooth Plateau block, which was tilted in the opposite direction. Toward the western end of the fault zone it has been elevated above the neighboring South Snowy block. On its northeast side the dip slope of the North Snowy block and those of the associated minor structures form an irregular mountain front facing the plains. The area considered in this report lies partly in the northwest corner of the North Snowy block and partly immediately to the north and west of it.



## DESCRIPTION OF THE STRUCTURES IN THE AREA

## GENERAL

Every one of the structures mapped in the Livingston Peak area was formed either directly or indirectly by lateral compression during the Laramide revolution. Folding, faulting, and lateral shifting were the chief processes involved, with faulting predominant. The deformation occurred in two distinct stages. During the earlier stage compressive stresses, acting at considerable depth, thrust up the Beartooth Range and tilted its component blocks. Later other stresses, operating nearer the surface, produced the minor folded and faulted structures adjacent to the range.

## FAULTS

The major normal fault, separating the North Snowy block from the region of low structural relief west of it, was formed in the early stage of deformation. This fault, which is the only normal fault in the district, owes its inception to vertical stresses set up by deep-seated compression. During the later stage a large plainsward-dipping overthrust was developed, whose hanging-wall block has ridden up and around the northwestern corner of the range. Where the forward advance of this overthrust sheet was stopped by the range, secondary high-angle thrusts were developed within the sheet north of the main fault. The only thrust fault in the area to form in front of it lies west of the mountains and has no continuation across the normal fault bounding the range. One of the two tear faults in the area resulted from the differential forward movement of the hanging-wall block of the major thrust. The other was formed during the folding of an anticline, which was subsequently faulted by one of the larger secondary thrusts. The details of the fault pattern are too complex to be easily described. For these details the reader is referred to the geologic map of the area.

*Deep Creek Ridge normal fault.*—Although actually traceable for only  $1\frac{1}{2}$  miles from Deep Creek across Deep Creek Ridge to Suce Creek, this is one of the most important faults in the region. From Deep Creek to the summit of Deep Creek Ridge the trace of the fault trends N.  $25^{\circ}$  E. Northward, the trace swings steadily to the west until at Suce Creek its trend is N.  $35^{\circ}$  W. Where measure-



ments could be made, the dip of the fault plane was found to vary from  $80^{\circ}$  W. to vertical. Thus the arcuate trace of the fault is dependent upon change in strike rather than upon variation in topography. The eastern side of the Deep Creek Ridge fault has been uplifted relative to the western, bringing pre-Cambrian schists and gneisses in contact with the Madison limestone. To the north the fault is cut off by the Suce Creek thrust fault, while to the south it disappears beneath the Deep Creek terminal moraine.

South of the point where Deep Creek flows into the Yellowstone River, the Yellowstone Valley has a nearly straight south-southwest trend for over 15 miles. East of it lie the lofty pre-Cambrian mountains of the North Snowy block, whereas west of it there are only comparatively low ridges of Paleozoic and Mesozoic sedimentary rocks, which are largely covered by thick accumulations of Tertiary volcanic breccias and tuffs. These ridges are not normal hogback ridges dipping away from the high part of the Beartooth Range but are expressions of independent structures, which strike into the valley and hence lie at an angle to the front of the range. If the strike of the southern end of the Deep Creek Ridge fault were to be continued south-southwestward, the trace of the fault would lie beneath the alluvium of the Yellowstone Valley about a mile west of the western front of the range. Since an extension of this fault would not only logically explain the differences in the rocks on either side of the Yellowstone Valley, for many miles south of the area, but would also account for the abrupt western termination of the Beartooths, it has been extended to the southern boundary of the map.

*Suce Creek-Window thrust.*—This fault, which extends across the area in a general east-and-west direction, is the most important thrust fault in the region. It was formed after the main uplift of the range, for it cuts off the Deep Creek Ridge fault along which the North Snowy block was tilted. Along the eastern extent of the fault, where the forward shove encountered the western extremity of the Beartooth Range, the hanging-wall block of the thrust has ridden a short distance up the dip slope of the North Snowy block, whereas west of the retarding Beartooth buttress the thrust sheet has advanced unobstructed over a region of low structural relief. As a re-

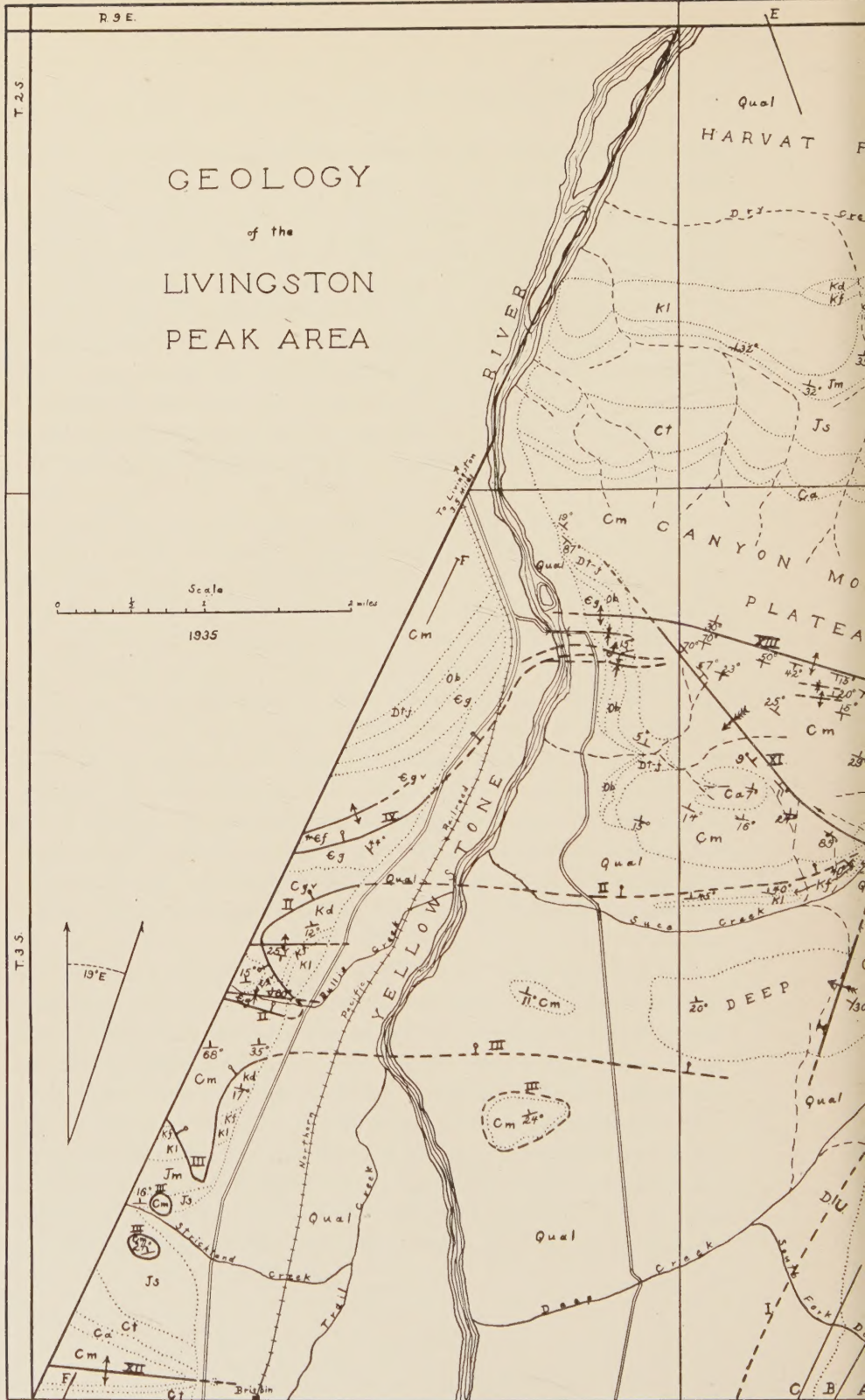
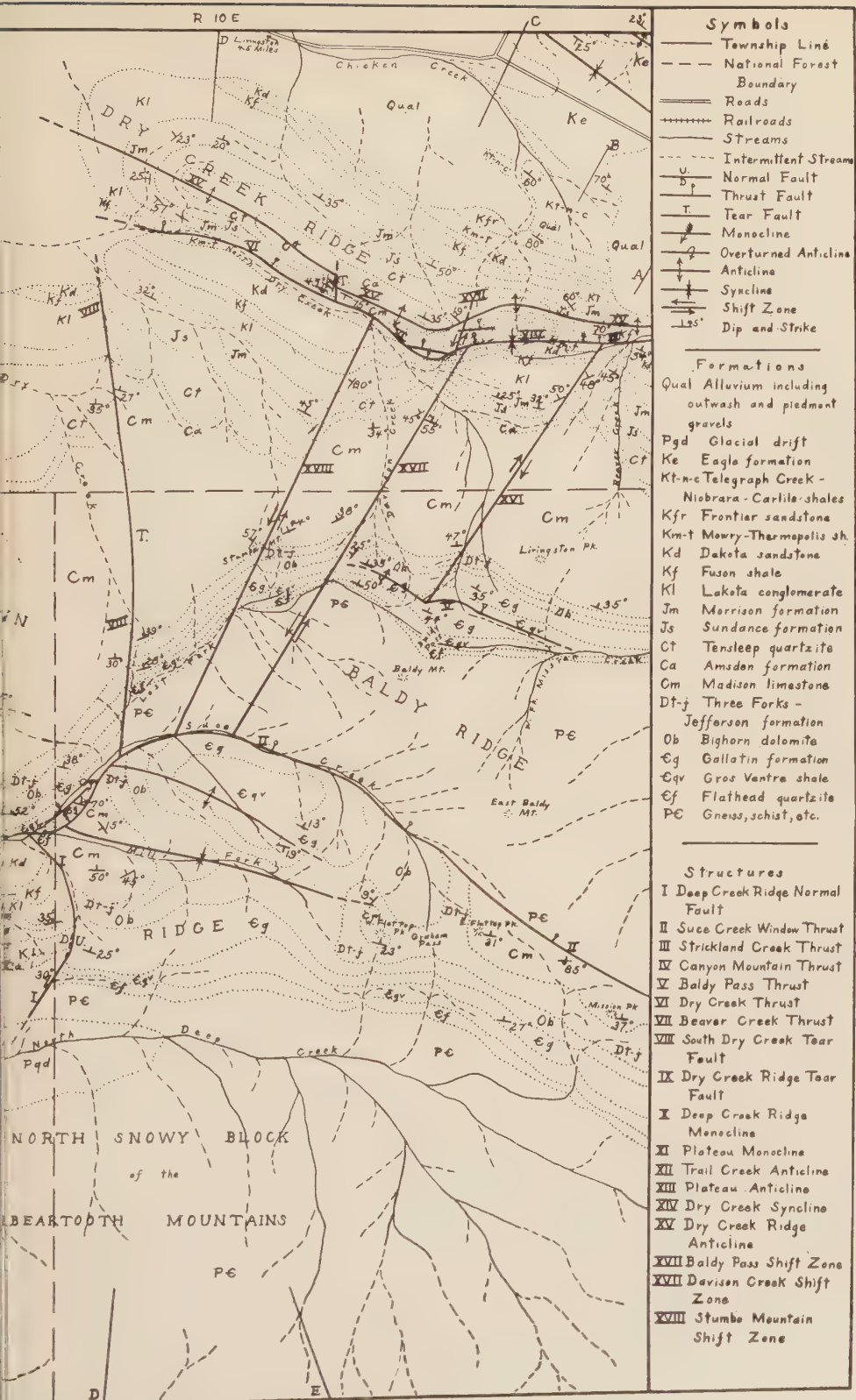


FIG. 2.—Geology of the





sult of this buttress in the foot wall of the thrust, actual displacement along the fault increases from east to west. The effect of the buttress is also manifest in great differences in the strikes and dips of the eastern and western sections of the fault.

West of the Yellowstone River, where it is known as the Window thrust, it is an extremely low-angle fault. At the mouth of Bullis Creek the Gallatin limestone has been thrust onto the Upper Madi-



FIG. 3.—The trace of the Suce Creek thrust fault. The upper part of the slope is underlain by dark-colored schists and gneisses of pre-Cambrian age, the lower slope by light-colored Madison limestone.

son limestone. North of Bullis Creek a post-thrust upwarp combined with subsequent erosion has caused the formation of a very large fenster, exposing the Mesozoic Lakota, Fuson, and Dakota formations surrounded by the Gallatin and Gros Ventre beds of the Cambrian. Although the upwarp has somewhat modified the original dip of the fault plane, it can be safely stated that the dip of the western section of the Suce Creek–Window thrust fault, even before warping, was not in excess of  $15^{\circ}$  N.

East of the Yellowstone Valley the trace of the thrust follows the main fork of Suce Creek to its headwaters north of East Flattop Mountain and thence follows the southern slope of Baldy Ridge to the eastern boundary of the area. Near East Flattop Mountain the

fault strikes N.  $70^{\circ}$  W. and has an apparent dip of about  $55^{\circ}$  N. The stratigraphic displacement along this part of the fault varies greatly as a result of the differential forward movement of the several sections of the hanging-wall block.

*Strickland Creek thrust.*—Another thrust fault of large stratigraphic displacement, but of less importance, is the Strickland Creek thrust, which comes to the surface north of Strickland Creek. It is similar in strike and dip to the western section of the Suce Creek–Window thrust. The upper block of the fault, which is entirely composed of Madison limestone, has overridden several Mesozoic formations.

*Canyon Mountain thrust.*—This fault differs from the other thrusts west of the Yellowstone River in having a steeper dip and a smaller stratigraphic displacement. Although the fault plane cannot be actually observed, the comparative regularity of its trace across the south slope of Canyon Mountain indicates that the fault is not a typical low-angle thrust. Where the displacement is greatest, the Gros Ventre formation has been thrust onto the Upper Gallatin limestone.

*Baldy Pass thrust.*—Located less than a half-mile northeast of Baldy Pass, this fault resembles the Canyon Mountain thrust in many ways. It is a high-angle thrust of small displacement involving only Cambrian formations.

*Dry Creek and Beaver Creek thrusts.*—Striking parallel to the Baldy Pass thrust and lying northwest of it is the Dry Creek thrust, which has been traced from the southeastern corner of Harvat flat about 2 miles up the valley of Dry Creek to where it passes into the Dry Creek syncline. Like the Baldy Pass thrust and the eastern section of the Suce Creek–Window thrust it is a high-angle fault. The Beaver Creek thrust is essentially a continuation of the Dry Creek fault to which it is linked by the Dry Creek syncline.

*South Dry Creek tear fault.*—Named because it lies almost entirely within the drainage basin of the south fork of Dry Creek, this fault strikes north and south and has a nearly vertical dip. Its trace runs northward from the valley of Suce Creek over the ridge between Livingston Peak and Canyon Mountain to the southeastern corner

of Harvat flat. The tear is limited to the Suce Creek thrust sheet and was formed at the time of thrust faulting.

The western side of the South Dry Creek tear fault has moved south relative to its eastern side. As a result of this movement the actual displacement on the Suce Creek thrust fault is decidedly greater west of the tear than east of it. The difference in crustal shortening on the two sides of the tear, arising from this differential displacement on the thrust, is equalized farther north by the Dry Creek Ridge anticline, which plunges westward at the eastern edge of Harvat flat and hence just east of the northward extension of the tear beneath the gravels of the flat.

*Dry Creek Ridge tear fault.*—This fault was formed during the folding of the Dry Creek Ridge anticline. When folding occurred, the section of the anticline west of the tear was relatively less compressed than the section east of it, the change in the amount of compression taking place at the fault. The Dry Creek Ridge tear has been cut off at its southern end by the Dry Creek thrust, and hence is known to be older than that structure.

#### FLEXURES AND FOLDS

During the early stage of the orogeny two monoclines were formed in the Livingston Peak area. One of these is the structural continuation of the Deep Creek Ridge normal fault north of the trace of the Suce Creek thrust. The other, which lies south of the trace of the thrust, parallels the normal fault. In the later stage of deformation several anticlines and synclines, a broad upwarp, and a downwarp were produced by shallow compressive stresses.

*Plateau and Deep Creek Ridge monoclines.*—Striking N. 40° W. the Plateau monocline has been traced from the Suce Creek thrust fault across Canyon Mountain Plateau to the Lower Canyon of the Yellowstone River. For the following reasons it is believed that this monocline was once continuous with the Deep Creek Ridge normal fault. The strike of the flexure is nearly the same as that of the northern end of the fault. The displacement on the two structures is similar not only in direction but also in amount. The displacement on the normal fault at its intersection with the Suce Creek thrust is so large as to necessitate a continuation of the structure north of the thrust.



The Deep Creek Ridge monocline parallels the Deep Creek Ridge fault and was probably formed by the same stresses. This flexure has a small displacement and there is no continuation of it north of the trace of the Suce Creek thrust.

*Trail Creek anticline.*—In the southwestern corner of the area a high limestone ridge projects into the Yellowstone Valley, the crest of which is formed by the core of an asymmetrical anticline. It has been named the Trail Creek anticline for the stream which flows along its southern flank west of the area, where it has been overturned and thrust-faulted.

There is at present a decrease in the intensity of deformation southward from the trace of the Suce Creek–Window thrust: the Strickland Creek thrust fault has a measurable displacement of almost a mile; the Trail Creek anticline has locally been ruptured by a thrust fault of considerably less displacement; no thrust fault is known to occur south of this fold. Hence it is believed that the folding and faulting south of the trace of the Suce Creek–Window thrust fault were probably caused by the southward advance of the hanging-wall block of this thrust.

*Open folds on the dip slope of the North Snowy block.*—In the southern part of the Suce Creek drainage basin, on the dip slope of the North Snowy block, are located a broad low anticline and a syncline. The strike of these folds is parallel to the average strike of the four thrust faults east of the Yellowstone River. Both folds are most compressed near their western ends. The actual displacement on the Suce Creek thrust also increases westward. These similarities strongly suggest that the folds, like the Trail Creek anticline, were formed by the unbalanced stresses involved in the forward movement of the Suce Creek–Window overthrust sheet.

*Dry Creek syncline.*—Striking east and west, this structure links the Dry Creek thrust fault to the Beaver Creek thrust. The beds forming the northern limb of the syncline have been thinned to less than one-third of their original thickness by stretching, which resulted from the thrusting that produced the Dry Creek and Beaver Creek thrust faults. The beds on this limb vary in dip between  $70^{\circ}$  S. and vertical, while those on the southern limb dip  $30^{\circ}$  N.

*Dry Creek Ridge anticline.*—This anticline, which holds up Dry Creek Ridge, is a very complex structure. From west to east it

passes from a broad open anticline into a nearly isoclinal fold. The structure has been thrust-faulted to the south at both ends, and where thrust faulting has not occurred, the southern limb of the fold has been stretched and thinned by the thrusting.

*Warping west of the Yellowstone River.*—West of the Yellowstone River near the mouth of Bullis Creek an upwarp and a downwarp have deformed the fault plane of the Suce Creek–Window thrust. The downwarp controls the course of Bullis Creek. The upwarp lies north of this creek and is partially responsible for the large fenster in the thrust sheet, which exposes the Lakota, Fuson, and Dakota



FIG. 4.—The western end of the Dry Creek Ridge anticline

formations surrounded by the Gallatin limestone and the Gros Ventre shale.

Since the fault plane prior to warping probably had a fairly uniform northward dip, the upwarp must be asymmetrical in cross section, its southern limb having the steeper dip. From the cross section of the upwarp something can be learned as to the nature of the stress which produced it. The structure was probably formed by a force couple in which the higher force was directed toward the south. As a movement on the Canyon Mountain thrust fault, whose trace lies a short distance north of the upwarp, would set up a force couple of this type, it is believed that the warping resulted from the southward advance of the Canyon Mountain thrust sheet.

The downwarp is so closely related to the upwarp that little need be said about it. It, too, is asymmetrical in cross section and was doubtless formed by the same stress that produced the upwarp.

## SHIFT ZONES

"Shift" is a general term used to describe the displacement of masses on either side of a complicated shear or fault zone, better termed a "shift zone." The three zones in the Livingston Peak area are homologous to tear faults, the only difference being that in the case of tear faults shearing takes place on a single plane, whereas in the case of shift zones shearing is distributed throughout a zone bounded by two parallel planes.

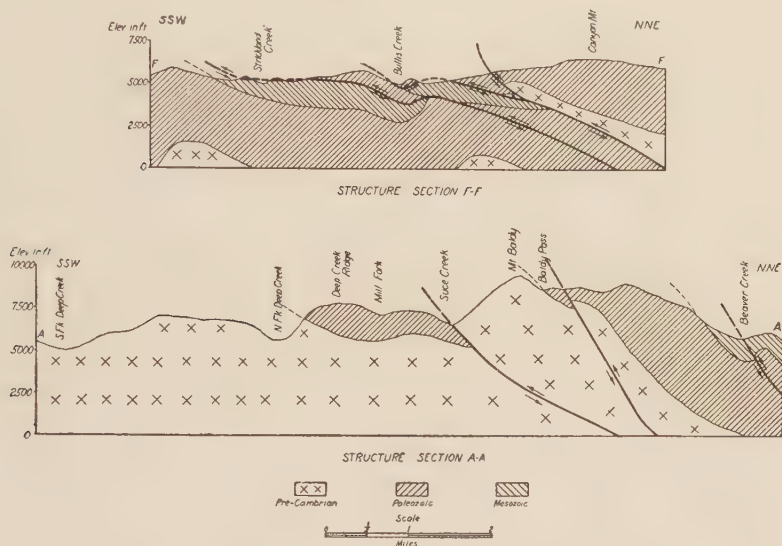


FIG. 5.—Structure sections in the Livingston Peak area

Certain characteristics of these zones make them easily discernible in the field. At the edge of a zone there is a change in the strike of the beds involved. Within the zone the less competent shales and sandstones have been thinned by stretching, and the more competent limestones and quartzites have been brecciated and displaced by numerous very small faults. The lines on the map (Fig. 2) showing the strikes and positions of the zones, which are mostly only a few hundred yards wide, were drawn as nearly as possible through the middle of each zone.

*Baldy Pass shift zone.*—This shift zone, which strikes N.  $35^{\circ}$  E., extends from the western end of the Baldy Pass thrust fault north-



eastward to the Beaver Creek thrust. About 300 yards west of the junction of the shift zone and the Baldy Pass thrust, the thrust fault passes into an overturned anticline. Since there was considerable differential movement in the hanging-wall block of this thrust and none in the foot-wall block, the former was the active block. It is obvious that the displacement of an active block increases laterally from the end of a thrust toward its central portion. Thus, since a large part of the differential movement in the active block of the Baldy Pass thrust near its western end occurred on the Baldy Pass shift zone, the eastern side of this zone must have been displaced southward with respect to the western. The swing in the outcrop pattern of every formation in crossing the zone is such that the outcrops of the formations west of the zone appear to have been shifted southward relative to those east of it. This difference in direction between the stratigraphic shift and the actual shift is to be expected, for the Baldy Pass thrust is a high-angle fault, whereas beds in the hanging wall of the thrust, excluding those in the shift zone, have an average dip of about  $35^{\circ}$  NE.

*Davison Creek shift zone.*—Lying about  $\frac{3}{4}$  mile west of the Baldy Pass shift zone and striking N.  $30^{\circ}$  E. is the Davison Creek shift zone, the western side of which has been displaced southward. In this case the stratigraphic shift and the actual shift are in the same direction. The Davison Creek shift zone was produced by differential movement on the Suce Creek thrust fault, the part of the thrust sheet west of the zone having been overthrust farther to the south than the part east of it. The resulting difference in displacement and in crustal shortening, on either side of the zone, is equalized north of the Dry Creek thrust fault on the northern limb of the Dry Creek Ridge anticline. North of the junction of the shift zone and the thrust there is a broad poorly defined shift zone in the anticline, whose western side has also been displaced southward. The difference in crustal shortening on the two sides of this zone, which was without doubt continuous with the Davison Creek shift zone prior to faulting on the Dry Creek thrust, is equalized to the north by the change in the dip of the northern limb of the anticline along its strike.

*Stumbo Mountain shift zone.*—The stratigraphic and actual shift on this zone are similar to those on the Davison Creek shift zone.

The difference in crustal shortening on the two sides of the Stumbo Mountain shift zone is also equalized north of the Dry Creek thrust fault. The Dry Creek Ridge tear fault is located a short distance west of the junction of the shift zone and the thrust. The section of the Dry Creek Ridge anticline east of the tear was more compressed than the section west of it. This difference in crustal shortening on the two sides of the tear is the opposite of that on the two sides of the shift zone and compensates it.

#### CHRONOLOGICAL SEQUENCE OF THE STRUCTURES IN THE AREA

##### GENERAL

The structures in the Livingston Peak area were developed during two distinct stages of the Laramide revolution which were separated by a considerable interval of time. The structures produced during the early stage were formed by deep-seated stresses, whereas those developed in the later stage were formed by stresses acting at no great depth. The later stage may itself be divided into two sub-stages, during each of which a group of essentially contemporaneous structures developed. It should be noted, however, that the chronological sequence to be described is based entirely upon structural evidence, for no Tertiary or late Upper Cretaceous strata, by means of which the orogenic movements might be dated, occur within the area.

##### STRUCTURES DEVELOPED IN THE EARLY STAGE

In this stage the North Snowy block of the Beartooth Mountains was strongly upthrust and tilted to the northeast. Most of the displacement along the western side of the block occurred on the Deep Creek Ridge normal fault which, during the early stage, passed northward without a break into the Plateau monocline. The remainder of the displacement occurred on the smaller Deep Creek Ridge monocline.

##### STRUCTURES DEVELOPED IN THE LATER STAGE

During the first substage of deformation the Suce Creek–Window overthrust fault was formed by comparatively shallow compressive stresses. This overthrust fault is known to have been developed after the upthrusting of the North Snowy block, for it has displaced the Deep Creek Ridge fault, along which the block was tilted.

When the thrust sheet advanced southward, its eastern section encountered the western extremity of the Beartooth Range and, after riding a short distance up the dip slope of the North Snowy block, was stopped by the obstruction. Further compression caused the western section, whose forward movement was relatively unobstructed, to be sheared from the remainder of the overthrust mass along the South Dry Creek tear fault, and the Stumbo Mountain and Davison Creek shift zones. There being no buttress to resist its southward advance, this section continued to move forward over the region of low structural relief west of the range until it was finally stopped by friction. Meanwhile the eastern section of the thrust sheet buckled, when subjected to further compression, giving rise to the development of the Dry Creek Ridge anticline, the Dry Creek syncline, the Baldy Pass thrust fault, and the Baldy Pass shift zone north of the Beartooth buttress.

After the Suce Creek-Window thrust sheet had been torn by horizontal shearing stresses, it was divided into four blocks by the South Dry Creek tear, and the Stumbo Mountain and Davison Creek shift zones. The southward displacement of each of these blocks is greater than that of the adjoining block east of it and less than that of the block west of it. This westward increase in the amount of displacement is largely equalized to the north by the eastward increase in the amount of compression of the complex Dry Creek Ridge anticline. Hence the folding of this anticline, and of the associated Dry Creek syncline, must have occurred simultaneously with the tearing of the major thrust sheet.

The Baldy Pass shift zone differs from the other shift zones in having the direction of shift reversed and in not extending to the trace of the Suce Creek thrust fault. Despite these differences, it is believed to have been formed at about the same time as the others for the following reasons. The Dry Creek thrust fault has displaced the northern end of the Davison Creek shift zone and the structural continuation of the Stumbo Mountain shift zone—the Dry Creek Ridge tear fault. The Beaver Creek thrust fault, which is the structural continuation of the Dry Creek thrust, has cut off the northern end of the Baldy Pass shift zone. From these relationships it can be seen that the three shift zones must have been formed at about



the same time, for they all preceded the thrusting which produced the thrust faults mentioned. Since the Baldy Pass shift zone was formed by the differential forward movement of the Baldy Pass thrust sheet, the Baldy Pass thrust fault must also be essentially contemporaneous with it.

In the foot-wall block of the Suce Creek–Window overthrust there are several structures which were formed by the unbalanced stresses involved in the southward advance of the thrust sheet and are therefore contemporaneous with the overthrusting. East of the Yellowstone Valley the open folds on the dip slope of the North Snowy block were produced in this way. West of the Yellowstone Valley the Strickland Creek thrust fault was developed, and the Trail Creek anticline was folded and, in places, overturned and thrust-faulted.

The first substage of the later stage of deformation ended when the Suce Creek–Window thrust sheet ceased to move southward, its eastern section having been stopped by the Beartooth buttress and its western section having been stopped by friction. Renewed compression caused the development of another group of structures north of the trace of this thrust fault, the formation of which occurred in the second substage. Although it is possible that these two substages may overlap somewhat, it can be proved that the structures of the first were at least close to completion before those of the second were initiated.

The Canyon Mountain thrust fault resulted from the buckling of the westernmost part of the Suce Creek–Window thrust sheet after this part had been stopped by friction. Since this part of the thrust sheet was the last to stop, this structure must have been formed after the first substage had ended. South of the trace of the Canyon Mountain thrust fault one may observe a upwarp and a downwarp of the fault plane of the major thrust. It is obvious that this warping also must have occurred after the first substage had closed.

Evidence has already been presented to show that the thrusting which produced the Dry Creek and Beaver Creek thrust faults occurred after the completion of the three shift zones. Since these shift zones were active throughout the greater part of the first substage, this thrusting must have taken place in the second substage.

## OVERTHRUSTING VERSUS UNDERTHRUSTING

An overthrust is by definition a thrust fault whose hanging wall has moved up the dip of the fault plane during thrusting. Conversely an underthrust is a thrust fault whose foot wall has moved down the dip of the fault plane during thrusting. It is possible, though perhaps less likely, that a combination of these movements may occur, in which case the fault cannot be classified as either an overthrust or an underthrust but must be designated simply as a thrust.

The displacement on a thrust fault increases laterally along its strike from none at its ends toward the central part of the structure. Thus the central section of at least one of the blocks must have moved a greater distance over or under the other block than has either of its end sections. During the differential forward advance of this block horizontal shearing stresses would be set up within it parallel to its direction of movement. In cases where these have caused tear faults or shift zones, such structures may be used to determine whether the hanging wall or the foot wall of the thrust fault was the active block during thrusting.

A tear fault, which is limited to one block of a thrust fault, is safely interpreted in only two ways. It must have been formed either at the time of thrust faulting or before thrust faulting was initiated. If the tear was formed at the time of thrust faulting, the block in which it is located must have been the active block of the thrust fault, for the existence of the tear fault proves differential advance and active slip within this block. Since it is rather unlikely that a thrust fault would displace an earlier tear in such a way that later only one end of the tear fault would be observed at the surface, it seems safe to state that a tear fault (or shift zone) limited to the upper block of a thrust fault is probably indicative of overthrusting, whereas one limited to the lower block is probably indicative of underthrusting. This criterion was suggested and first used by Charles W. Wilson, Jr., in his report on the thrust fault near Gardiner, Montana.<sup>1</sup>

*Suce Creek-Window thrust fault.*—There are two shift zones and one tear fault limited to the hanging-wall block of the Suce Creek—

<sup>1</sup> "Geology of the Thrust Fault near Gardiner, Montana," *Jour. Geol.*, Vol. XLII (1934), p. 656.

Window thrust fault. If these structures had been produced before thrust faulting was initiated, one would naturally expect to find similar structures in the foot-wall block of the thrust. No tear structures have been observed, however, for many miles south of the trace of the thrust fault. Hence this fault is probably an overthrust.

The strike of the Suce Creek–Window thrust fault near the eastern boundary of the Livingston Peak area is N.  $70^{\circ}$  W., whereas at the western boundary it is N.  $80^{\circ}$  E. This change in strike takes place gradually. The strikes of the three tear structures in the overriding block of the thrust fault are, from east to west, N.  $30^{\circ}$  E., N.  $25^{\circ}$  E., and north-south. Thus each of the tear structures joins the thrust fault at an angle closely approximating  $90^{\circ}$ . If the tear structures were formed by shearing stresses set up in an overthrust sheet parallel to its movement, they would ideally join the thrust fault at an angle of  $90^{\circ}$ .

The three tear structures in the Suce Creek–Window thrust sheet radiate from a relatively small area within the northwestern corner of the North Snowy block. If the thrust fault is assumed to be an overthrust, this unusual radial pattern can easily be explained. An overthrust sheet which encountered a buttress, such as the North Snowy block is known to have constituted, would tend to pivot around this buttress. Tearing of the overthrust sheet would result from the differential resistance offered by the buttress to its forward advance. The net result of this pivoting and tearing would be that, after compression had ceased, the tear faults and shift zones in the overthrust sheet would radiate from the corner of the buttress.

It seems utterly impossible that these intimate relationships between the three tear structures in the Suce Creek–Window thrust sheet and the Suce Creek–Window thrust fault would exist if the tear structures had been formed before thrust faulting was initiated. Therefore it seems safe to conclude that the Suce Creek–Window thrust fault is an overthrust.

During part of the summer of 1935, C. W. Wilson, Jr., mapped the eastern end of this thrust fault where it passes into an over-turned fold near the West Boulder River. After applying the criterion proposed by T. S. Lovering on the swing of the strike of the



strata associated with the passage of a thrust fault into a fold, he too concluded that the fault was an overthrust.<sup>2</sup>

*Baldy Pass thrust fault.*—The Baldy Pass shift zone, which is limited to the hanging-wall block of the Baldy Pass thrust fault, joins the thrust at an angle of about  $75^{\circ}$ . There are no shift zones or tear faults south of the trace of the thrust. Hence this fault is probably an overthrust.

*Dry Creek and Beaver Creek thrust faults.*—Near its passage into the Dry Creek syncline the Dry Creek thrust fault has displaced the Davison Creek shift zone. The displaced sections of this zone are similar in that on both of them the amount of shift decreases toward the north. The amount of shift on the northern section, however, is much greater than that on the southern section. This discrepancy can be explained only if it is assumed that movement on the northern section was renewed during the development of the Dry Creek thrust fault. As the northern section of this zone lies in the hanging-wall block of the Dry Creek thrust fault, this fault must be an overthrust. The Dry Creek and Beaver thrust faults are parts of the same structural lineament and have similar dips and strikes. Therefore the Beaver Creek thrust must also be an overthrust.

*Canyon Mountain and Strickland Creek thrust faults.*—As no shift zones or tear faults have been observed in the western part of the Livingston Peak area, where these faults are located, and as neither of these faults can actually be traced laterally into an overturned fold, they cannot be definitely classified as either overthrusts or underthrusts. Each of them, however, resembles in many respects one or more of the thrust faults already discussed. Therefore it is believed that they likewise are probably overthrusts.

#### MECHANICS OF DEFORMATION

##### THE UPLIFT OF THE NORTH SNOWY BLOCK

*The stresses involved.*—If, when deep-seated lateral compression takes place, there are zones of weakness in the earth's outer crust, the mass subjected to compression will tend to elongate vertically

<sup>2</sup> C. W. Wilson, Jr., personal communication; T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), pp. 651-663.

in these zones, lifting a portion of the outer crust against gravity. Since the North Snowy block of the Beartooth Range is bounded on two sides by nearly vertical faults, it seems likely that it was uplifted in this way.

*Pre-existing zones of weakness.*—The North Snowy block is bounded on its western side by a high-angle fault, which strikes N. 25° E., and on its southern side by a zone of steeply inclined faults, which trends about east and west. These directions have more than local significance, for it has been observed that

throughout the [Beartooth-Bighorn] region the axes of the major uplifts and of anticlines, of flexures, and of overthrust mountain borders tend to follow one of three directions which dominate the whole structural pattern. These are N. 25° W., about N. 20° E., and east-west.<sup>3</sup>

The simplicity of this pattern strongly suggests that the boundaries of the blocklike uplifts in the region were controlled by a pre-existing system of linear zones of weakness. Since there was little diastrophism in this region during the Paleozoic and Mesozoic eras, these linear zones of weakness must have been formed in the pre-Cambrian.

In 1933 Drs. Ernst and Hans Cloos studied the pre-Cambrian structure of the Beartooth, Bighorn, and Black Hills uplifts. They noted that "though differing individually in every detail, the three structural units seem to indicate coincidence between pre-Cambrian doming and their present boundaries."<sup>4</sup>

The pre-Cambrian structure of the western part of the Beartooth Range has not as yet been studied in detail. There is evidence, however, that the Deep Creek Ridge normal fault, which bounds the North Snowy block on its western side, coincides with a pre-Cambrian zone of weakness.

Between Mill Creek and the northwestern corner of Yellowstone National Park is a striking alinement of hot springs and large extinct volcanoes. This alinement, which trends between N. 20° E. and N. 25° E., includes Chico and Corwin hot springs, the basic sills in

<sup>3</sup> W. H. Bucher, W. T. Thom, Jr., and R. T. Chamberlin, "Geologic Problems of the Beartooth-Bighorn Region," *Geol. Soc. Amer. Bull.* 45 (1934), p. 175.

<sup>4</sup> "Pre-Cambrian Structures in the Beartooth, Bighorn, and Black Hills Uplifts, and Its Coincidence with Tertiary Uplifting," *Geol. Soc. Amer. Proc. for 1934*, p. 56.

Cinnabar Mountain, and Electric and Emigrant peaks, which are erosional remnants of extinct volcanoes. This alinement of magmatic and hot-water conduits crosses the pre-Cambrian core of the South Snowy block. Since there is no Laramide faulting in this section of the South Snowy block, the alinement must have been controlled by a linear zone of weakness in the pre-Cambrian rocks. If this zone of weakness were projected to the north-northeast of Mill Creek, it would parallel the western face of the North Snowy block and would lie about a mile west of the mountain front. It has already been shown that, if the southern end of the Deep Creek Ridge normal fault were projected south-southwest of Deep Creek, it would parallel the mountain front and would lie about a mile west of it. Therefore it is believed that the same zone of weakness determined the position of both the normal fault and the series of hot springs and extinct volcanoes. Substantiating this belief is the fact that the only hot-spring deposit in the Livingston Peak area is located on the eastern side of the Lower Canyon of the Yellowstone River at the northern end of the Plateau monocline, which is the northern structural continuation of the Deep Creek Ridge normal fault.

There are no known hot springs or large extinct volcanoes for many miles west of this zone of weakness as defined above. There are, however, two groups of intrusives east of it, which are located in the Mill Creek basin and along the northern front of the range. The writer believes that these groups are probably in some way related to other zones of weakness, one of which determined the position of the fault zone on the southern side of the North Snowy block.

Thus, before deep-seated compression took place, the segment of the earth's crust which now forms the North Snowy block of the Beartooth Range was probably partially outlined on at least three sides by zones of weakness. For this reason, when deep-seated compression did occur, this segment offered relatively little resistance to upthrusting. Since it is very improbable that a block would ever be uniformly uplifted by upthrusting, the fact that the North Snowy block is at present tilted to the northeast needs no further explanation.



## INITIATION OF THE SUCE CREEK-WINDOW THRUST FAULT

*Preceding structure.*—It is known that the western part of the Suce Creek–Window thrust fault was developed from an overturned anticline, for it has been traced laterally into this type of structure near the West Boulder River. This anticline must have been located near the base of the North Snowy block, because the Plateau monocline, along which the block was uplifted, terminates a short distance north of the present trace of the thrust fault.

The origin of this anticline is easily explained. When a segment of the earth's crust is bent upward by lateral compression, such minor folds as develop tend to have the same symmetry, or asymmetry, as the major uplift, like drag folds on the limbs of ordinary anticlines. If the anticline which preceded the Suce Creek–Window thrust fault was formed in this way, one would expect to find similar folds to the east of it. East of the West Boulder River there is a large anticline which parallels the mountain front. This anticline has also been deformed by a plainsward-dipping thrust fault of large displacement.

*Stresses involved in the formation of the thrust fault.*—At the beginning of the later stage of the Laramide revolution the upper surface of the pre-Cambrian of the North Snowy block sloped at a low angle toward the northeast. Near the base of the block this surface was folded into an anticline whose southwestern flank was much steeper than its northeastern flank. West of the North Snowy block, however, the upper surface of the pre-Cambrian was essentially flat.

When the region was subjected to shallow compressive stresses, these stresses were influenced by the structures just described and two stress couples were set up. The greater of these tended to push the North Snowy block north-northeastward over the region of low structural relief north of the range. The lesser tended to push the anticline at the base of the block toward the south-southwest. Owing to the difference in size between the anticline and the uplifted block, the anticline was more easily deformed. The initial asymmetry of the anticline caused the thrust fault, which was developed, to dip toward the north-northeast. The angle of dip of the thrust fault, however, was controlled by the greater stress couple. This

couple rotated the shearing plane, along which the fault broke, toward the vertical. Consequently the dip of the eastern section of the thrust fault is considerably in excess of the  $45^\circ$  angle at which thrust faults should theoretically break. West of the North Snowy block, however, where only the lesser stress couple was active, the dip of the thrust fault is much lower.

DEFORMATION DURING THE DEVELOPMENT OF THE SUCE  
CREEK-WINDOW THRUST

Because of the lower dip of the western section of the Suce Creek-Window thrust fault, the western part of the overthrust sheet was more easily moved than the eastern part. As a result there is at present a westward increase in the amount of displacement on the fault. This increase in displacement is equalized north of the trace of the thrust by the westward decrease in the amount of crustal shortening observed in the group of structures which developed in the overriding block of the thrust during the first substage of the later stage of deformation.

As there is a tendency for an advancing overthrust sheet to drag its foot wall along with it, one would expect to find the most deformation in the western section of the foot-wall block of the Suce Creek-Window thrust, because the greatest amount of displacement is observed on the western section of this fault. Such is the case, for a marked westward increase in the amount of crustal shortening is found in the group of structures located south of the trace of the major thrust fault. One effect of this increase is the change in the strike of the thrust fault from N.  $70^\circ$  W. on the southern slope of Baldy Ridge to N.  $80^\circ$  E. west of the Yellowstone River. Another effect is the radial pattern of the tear structures in the overthrust sheet.

DEFORMATION AFTER THE COMPLETION OF THE  
SUCE CREEK-WINDOW THRUST

At the end of the first substage of the later stage of deformation there existed a westward decrease in the amount of crustal shortening in the overthrust sheet of the Suce Creek-Window thrust fault. Hence, when lateral compression was renewed, the western part of the thrust sheet offered less resistance to further deformation than

did the eastern part. As a result it was more deformed, and a westward increase in the amount of crustal shortening in the series of structures produced in the closing substage of the orogeny is now observed.

#### THE BEARTOOTH BUTTRESS

The Beartooth butters resembles in many respects the better-known Adirondack butters, which controlled the trends and grouping of the thrust faults and folds in the northern Appalachians, and the well-known Black Forest butters, around which were deflected the folds of the Jura Mountains. All three of these butters are structural uplifts formed by deep-seated stresses, and are larger and older than the folded and faulted structures adjacent to them.

It has been shown that the North Snowy block of the Beartooth Mountains acted as a butters in the later stage of the Laramide orogeny largely because of its high structural elevation and relatively great size. Inherent rigidity of the rocks, which is so frequently referred to in the descriptions of other butters, could have played but a small part in the butters action of this block, for crystalline rocks are found not only in the butters but also in the overthrust sheet, whose forward advance the butters obstructed.

#### PRESSURE-BOX EXPERIMENTS

During the spring of 1935 the writer performed several pressure-box experiments in the structural laboratory of the University of Chicago, the purpose of which was to find out what might happen when an advancing overthrust sheet encounters a butters like that in the Livingston Peak area. Professor R. T. Chamberlin supervised the experiments and aided the writer in their interpretation.

*Apparatus.*—The pressure box in which the experiments were carried out has a square base, measuring 19 inches on a side, and is 4 inches deep. The pressure was applied by means of a push block propelled by a powerful jackscrew. Since the push block was not attached to the screw, it was free to pivot when differential resistance to its forward movement was encountered. When the resistance was equal, however, the push block did not pivot, since the screw was in contact with the central part of the block. Damp sand



was used in the experiments, because it is easily molded and has a uniform composition.

*Setup for the experiments.*—The same experiment was repeated fourteen times. In order to facilitate a description of it and to give the proper orientation, the movable side of the pressure box will be called the “northern side.” A mound of sand, 4 inches high, was built in the southeast corner of the box. The larger part of the surface of this mound sloped to the north at an angle of about  $20^{\circ}$ , simulating the Beartooth buttress. Near the western edge of the mound the surface sloped at an angle of about  $80^{\circ}$  to the west like the North Snowy block. In the northern half of the box an east-west asymmetrical anticline was built, whose crest had a height of about  $1\frac{1}{2}$  inches. This represented the anticline which preceded the Suce Creek–Window thrust fault. The steeper limb of this anticline faced south. The remainder of the box was filled with sand to a depth of 1 inch. Before pressure was applied, the damp sand was compacted by patting it with the palm of the hand.

*Results.*—When pressure was initiated, the low anticline was broken in every case by a northward-dipping overthrust fault. Upon the application of further pressure the overthrust sheet advanced southward, its eastern section riding up the dip slope of the mound in the southeastern corner of the pressure box. Near the western edge of the mound the thrust sheet was generally broken by several small tear faults. In the five out of the fourteen experiments in which these faults were well developed, it was observed that the upper surface of the eastern section of the thrust sheet was no longer a plane surface but had been slightly warped.

When still further pressure was applied, the push block pivoted, its western end moving forward more rapidly. Coincident with the pivoting of the push block a number of small northward-dipping overthrust faults developed in the southwestern corner of the pressure box south of the trace of the major thrust.

*Conclusion.*—When these experiments were undertaken, it was fully realized that the results obtained would be suggestive rather than conclusive. The structural pattern produced in the pressure box, however, was so strikingly similar, even in its details, to that

observed in the Livingston Peak area that the writer feels justified in stressing the importance of the Beartooth buttress in the orogenic history of the Livingston Peak area.

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